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Changes in the Vertical Temperature Structure Associated with Carbonaceous Aerosols

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J1.18 CHANGES IN THE VERTICAL TEMPERATURE STRUCTURE ASSOCIATED WITH CARBONACEOUS AEROSOLS

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1. INTRODUCTION

Carbonaceous aerosols from anthropogenic activities act to both scatter and absorb solar radiation. It has been postulated that absorption by aerosols might significantly alter both the vertical temperature structure of the atmosphere and cloud fraction [Hansen et al. 1997, Ackerman et al. 2000]. Since both effects may alter the assessment of climate change associated with human activities, it is very important to understand both the magnitude and the mechanism by which carbonaceous aerosols affect climate.

In this paper, we used a coupled climate and chemistry transport model to estimate the effects of carbonaceous aerosols on the vertical temperature structure and their effects on cloud fraction. A series of control simulations were also carried out to compare the results of the model in which carbonaceous aerosols interact with climate with those in which they do not. We will present the temperature difference between simulations that include the effect of black carbon on the radiation field and those that do not, both at the surface and in the free troposphere. We will also discuss the change of temperature lapse rate and changes of cloud fraction associated with black carbon.

2. MODEL DESCRIPTION AND EXPERIMENT DESIGN

The model we used in this study is an updated version of the NCAR CCM1 climate model and GRANTOUR chemical transport model [Taylor and Penner 1994]. The climate model has been improved by adding the capability to treat absorption and scattering of radiation by black carbon and by biomass aerosols [Penner et al. 1998, Grant et al. 1999]. The GRANTOUR model is a 3-D lagrangian model of transport, transformation and removal. In the version of GRANTOUR used here, there are 48 x 42 horizontal grid points and 14 vertical levels. The biomass burning inventories used in this work were those developed by Liousse et al. [1996] and included savannah, forest, agriculture and domestic fires. The fossil fuel inventory of black carbon used was that developed by Penner et al. [1993]. For our model, we specify a dry specific mass absorption coefficient at 0.55 μm for fossil fuel black carbon of 7.34 m^2g^{-1}, while that for biomass burning black carbon is 7.8 m^2g^{-1} [Penner et al. 1998]. The relative humidity dependence of the absorption and scattering coefficients for biomass aerosols is that derived by Penner et al. [1998], while the absorption and scattering coefficients for black carbon from fossil fuel do not change with relative humidity. The absorption of solar radiation by black carbon leads to a positive forcing of 0.20 W m^{-2} at the TOA, while the forcing for aerosols from biomass burning is -0.14 W m^{-2} in this version of model [Penner et al. 1998]. Because of its strong absorption effect, black carbon can shift solar heating to the aerosol layer. Depending on the vertical distribution of black carbon, this may lead to a decrease in the vertical temperature lapse rate. The vertical temperature profile is also determined, in part, by the convection. Effects of black carbon on cloud amount or on the time averaged horizontal cloud cover (cloud fraction) may result from several effects: (1) Suppressed convection would mean that less water vapor is transported to the region where it might condense. (2) Cooling and warming effects may reduce or enhance evaporation of cloud drops, which may also influence the cloud fraction. (3) Reduced temperature at the surface may reduce evaporation of water, causing a decreased supply of water vapor for cloud formation.

To assess these effects, we carried out two five year simulations for each of the aerosol species in this study, one allowing black carbon to affect the radiation in the model, and one where black carbon did not interact with the radiation field. All results were performed with the version of the model with prescribed SSTs. The surface temperature reported below is that extrapolated from the model layers immediately above the surface.

First, the monthly average temperatures for the two five year simulations were calculated and compared at the surface and at 500 mb. Then the effect of black carbon on the temperature structure was evaluated. To evaluate the response of vertical temperature to black carbon, we first calculated the monthly average temperature lapse rate or temperature difference ΔT between the surface and 500 mb. The monthly average of black carbon column burden was also derived for each simulation. Next, anomalies were calculated by subtracting the five year monthly average of the surface and 500 mb temperature difference and black carbon column burden in each month from their monthly averages. The correlation between the temperature difference anomalies and the black carbon column burden anomalies was calculated

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at each grid point. The correlation was computed only for the grid points that had a column burden of black carbon that was greater than 2.0 x 10^{-4} mg m^{-2}. The correlation coefficient indicates how the vertical temperature structure responds to black carbon. If the temperature lapse rate or temperature difference ΔT decreases as black carbon column burden increases, then the correlation will be negative. This indicates a cooling at surface relative to the mid-troposphere temperature. Warming at surface relative to the mid-troposphere is associated with a positive correlation between the temperature difference anomalies and black carbon column burden anomalies. Here we examine the calculation of correlation coefficients for both the interactive and non-interactive simulations. The two results are compared to judge the effect of black carbon. Because absorption by black carbon may be expected to act in a fairly short time scale, we also included an analysis of the correlation of the daily temperature difference anomalies with the daily black carbon column burden anomalies. We also evaluated the change of stratoform cloud fraction using a similar approach to that employed in the analysis for temperature.

3. FOSSIL FUEL BLACK CARBON

In the experiment for fossil fuel black carbon, aerosols are released in the lowest 100 mb above the surface. Then they are transported by convection, diffusion and advection. The vertical profile of fossil fuel black carbon shows that on average most the fossil fuel black carbon remains in the boundary layer and mixing ratios drop very rapidly above that level. The maximum is therefore near the altitude where it is injected. As a result, the absorption by fossil fuel black carbon takes place near the surface. The major source regions for fossil fuel black carbon are Europe, Asia and North America. Figure 1 shows the average change in temperature at the surface between the interactive and non-interactive simulations. On average, the presence of fossil fuel black carbon tends to warm the surface. The surface temperature increase is between 0.0 - 0.5 degree in the winter and between 0.0 - 1.0 degree in the summer. Figure 2 shows the correlation coefficient between the black carbon anomalies and temperature difference anomalies for the simulation with interactive fossil fuel black carbon. In the major fossil fuel black carbon source region there is a positive correlation between the temperature difference anomalies and black carbon column burden anomalies. This correlation is absent in the simulation where fossil fuel black carbon is not allowed to interact with the radiation field. The difference of correlation coefficients in the two cases shows that the correlation increases by 0.2 to 0.5.

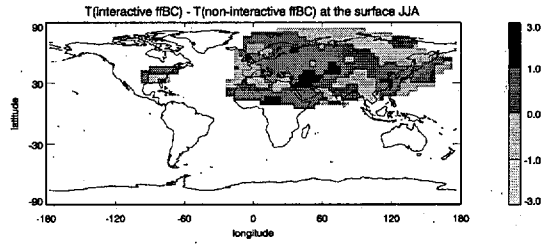

Figure 1. Temperature difference at the surface in the summer between the simulation for interactive fossil fuel black carbon and simulation for non-interactive fossil fuel black carbon.

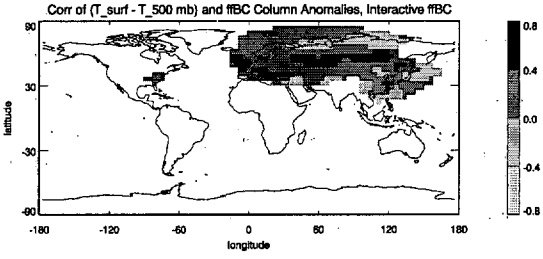

Figure 2. The correlation coefficients for the interactive fossil fuel black carbon simulation. Correlation coefficients are calculated between the anomalies of fossil fuel black carbon column burden and the anomalies of temperature difference between surface and 500 mb.

4. BIOMASS BLACK CARBON

The major source regions for biomass black carbon are in Africa, South America and Southeast Asia. In the case of biomass aerosols, to account for the injection at high altitude associated with plume rise, we injected biomass aerosols between 700 and 400 mb. Therefore, maximum mixing ratio for biomass black carbon is near 600 to 500 mb. While black carbon warms the aerosol layer by absorbing solar radiation, it also reduces the downward radiation flux at the surface, decreasing the surface temperature. Figure 3 shows the difference in temperature at the surface for the interactive simulation and non-interactive simulation. The temperature difference between the simulation that included the effects of biomass black carbon aerosols on the radiation and the simulation that did not shows that the surface is cooled by between -0.5 and -2.5 degrees. The temperature difference with and without biomass black carbon at 500 mb is less than 1.0 degree. This also results in a larger negative correlation between the temperature difference anomalies and black carbon column burden anomalies for the interactive simulation compared to the simulation where biomass black carbon is non-interactive (see Figure 4). This effect is especially evident over the ocean near Africa, Indonesia and East China. Over continental Africa, the negative correlation is not as large as over the ocean. This may indicate that convective mixing may affect the vertical temperature structure more than absorption by black carbon over the continental regions.

The daily analysis indicates a similar effect to the vertical temperature structure.

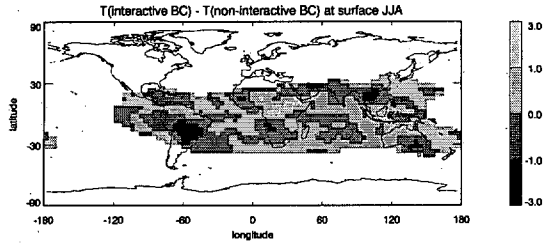

Figure 3. Temperature difference at the surface in the summer between the interactive simulation and non-interactive simulation for biomass burning.

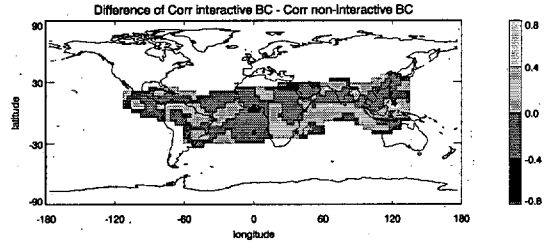

Figure 4. The difference of correlation coefficients for the interactive and non-interactive biomass carbon simulations. Correlation coefficients are calculated between the anomalies of biomass black carbon column burden and anomalies of temperature difference between the surface and 500 mb.

As noted above, absorption of solar radiation by black carbon may also influence the presence of clouds. This may act in two ways. First, if biomass black carbon cools the surface, the local evaporation of water may be suppressed. This can lead to a decrease of cloudiness near the surface. Second, if temperatures are decreased cloudiness may increase because saturation vapor pressures are reached more frequently. To examine this, we correlated the anomalies of stratoform cloud fraction and the black carbon concentration anomalies at each height between the surface and the tropopause. Figure 5 shows the difference of the correlation coefficient for the interactive and non-interactive cases at a sigma level of 0.9 and 0.5. The correlation of cloud fraction anomalies and black concentration anomalies is positive at sigma level of 0.9 and negative at sigma level of 0.5 in the interactive simulation. The difference of the correlation coefficient shows that at a height near 900 mb there is an increase in the correlation, while at a sigma level equal to 0.5, we can see that the negative correlation is stronger. The effect on cloud fraction is largest in African, South America and Indonesia. This suggests that in this model, biomass black carbon can influence cloud fraction due to its absorption of solar radiation and its effect on the temperature. Moreover, while the reduction of clouds at higher altitudes can decrease the amount of reflected solar radiation, the increase of cloudiness at low altitudes would increase reflected radiation. We tested the net effect of these opposing effects by calculating the forcing by black carbon for both the interactive and non-interactive simulations, no significant differences in forcing were found (see table 1).

Table 1. Forcing with and without interactive calculation of black carbon (w m^{-2})

Simulation	Forcing
Fossil fuel BC, interactive	+0.200
Fossil fuel BC, non-interactive	+0.199
Biomass burning smoke, interactive	-0.120
Biomass burning smoke, non-interactive	-0.122

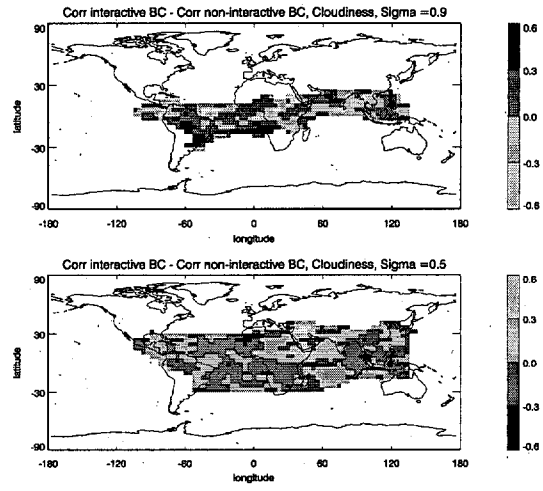

Figure 5. The difference of correlation coefficients for biomass black carbon at sigma equal to 0.9 and 0.5. Correlation coefficients were calculated between the biomass black carbon concentration anomalies and stratoform cloud fraction anomalies.

5. CONCLUSION

In this study we examined simulations of the improved version of NCAR CCM1 model and the GRANTOUR model to assess the effects of black carbon on temperature and cloud fraction. Fossil fuel black carbon tends to warms the surface relative to the mid-troposphere. The annual averaged temperature change in the interactive fossil fuel black carbon simulation compared to that in the non-interactive case over Europe is about 0.5 degree. Increases in black carbon at the surface can also increase the vertical temperature lapse rate. This was shown by comparing the correlation coefficients for the temperature difference anomalies and black carbon column anomalies in the interactive and non-interactive cases.

In contrast to fossil fuel black carbon, biomass carbon is released at a much higher level. Therefore, biomass black carbon cools the surface relative to the mid-troposphere in our model. The annual averaged surface temperature decrease is about - 0.5 to - 2.5 degrees between the interactive and non-interactive simulations.

We also found that the correlation of biomass black carbon column burden anomalies and the anomalies of temperature difference between the surface and the mid-troposphere was negative, indicating that the lapse rate was reduced. This effect was larger over the ocean than over the continents. Cloud fraction also responded to the change of temperature and to black carbon. Biomass black carbon reduces cloud fraction in the mid-troposphere while it increases cloud fraction at the surface.

At the meeting we will assess the significance of the change in the correlation coefficients on the vertical temperature structure and cloudiness. Then we can quantitatively evaluate these effects.

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